

OXIDE MATERIAL AND A FUEL CELL ELECTRODE CONTAINING  
SAID MATERIAL

5 The invention relates to a novel oxide material. The invention also relates to an electrode comprising such a material. Finally, the invention relates to a device for producing electrical energy of the fuel cell type comprising at least one electrochemical cell comprising a cathode which is such an electrode.

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A cell, or secondary battery such as an electrochemical cell, converts chemical energy into electrical energy. In a fuel cell, hydrogen, coming for example from any carbon-based fuel such as gas, a petroleum based oil  
15 product, or methanol, is combined with oxygen drawn from the air in order to produce electricity, water and heat by means of an electrochemical reaction. The core of the fuel cell is composed of an anode, a cathode and an electrolyte which is a solid ceramic-based  
20 electrolyte. The oxygen ions flow through the electrolyte and the electrical current flows from the cathode to the anode.

SOFCS (Solid Oxide Fuel Cells) are fuel cells that  
25 usually operate at high temperatures, of around 650 to 1000°C. They can be used in steady-state high-power (250 kW) and low-power (1 to 50 kW) supply systems. They are potentially advantageous owing to their high electrical efficiency (generally around 50 to 70%) and  
30 owing to the use of the heat that they produce.

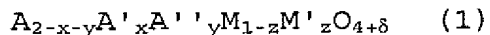
Current SOFC materials operate at temperatures of about 900 to 1000°C and will be explained below. The solid electrolyte most commonly used is yttrium-stabilized  
35 zirconia or YSZ. The anode, which is in particular the site of the reaction between  $H_2$  and the  $O^{2-}$  anions coming from the electrolyte, is most commonly a cermet (a metal/ceramic composite) of the type in which nickel

is dispersed in stabilized zirconia (YSZ), optionally doped with ruthenium Ru. The cathode, which collects the charges and is the site of the reduction of oxygen, which then diffuses in the  $O^{2-}$  anion state through the electrolyte, is most usually based on an oxide of perovskite structure, such as lanthanum manganite doped with strontium  $(La,Sr)MnO_{3\pm\delta}$ . Finally, bipolar plates, or interconnectors, are present, generally there being two of them, and their function is to collect the charges at the anode and at the cathode and to separate the two gases, namely fuel ( $H_2$ ) and oxidizer ( $O_2$ ).

Now, the operation of the cell at such a high temperature poses many problems, especially the cost of the interconnectors and the chemical and above all mechanical behavior of the materials at temperature. This is why it has been envisaged to lower the operating temperature of the cell to around 600-800°C. This would allow Inconel® (a heat-resistant alloy based on Ni, Cr and Fe) or stainless steels to be used as interconnectors. The electrolyte that has been envisaged for replacing YSZ is cerium oxide doped with gadolinium oxide,  $CeO_2:Gd_2O_3(Ce_{0.9}Gd_{0.1}O_{1.95})$  with a fluorite structure, or a substituted  $LaGaO_3$  perovskite  $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{2.85}$ . The anode could be based on vanadium chromite. As regards the cathode, various materials have been studied, including perovskites of the  $ABO_3$  type, and in particular doped  $LaMnO_3$  for reasons of good mechanical behavior, which may or may not be deficient on the A sites, and above all oxygen-deficient perovskites  $ABO_{3-\delta}$  such as  $(La,Sr)CoO_{3-\delta}$ . It remains the case that, at the present time, there is no material making it possible to use the cathode with, simultaneously, high electronic conductivity, a high ionic conductivity, good thermal stability and sufficient efficiency from the industrial standpoint.

It was to solve these problems of the prior art that another type of oxide material had to be sought. The material according to the invention does this.

- 5 The material according to the invention is an oxide material of the following general formula:



where:

- 10 A is a metal cation belonging to the group formed by lanthanides and/or alkali metals and/or alkaline-earth metals;

A' is at least one metal cation belonging to the group formed by lanthanides and/or alkali metals and/or alkaline-earth metals;

- 15 A'' is a cationic vacancy, that is to say a cation A and/or cation A' vacancy;

M is a metal belonging to the group formed by metals of the transition elements; and

- 20 M' is at least one metal belonging to the group formed by metals of the transition elements, said material being such that:

$$0 < y < 0.30, \text{ preferably } 0 < y \leq 0.20;$$

$$0 < \delta < 0.25, \text{ preferably } 0 < \delta < 0.10;$$

$$0 \leq x \leq 2; \text{ and}$$

- 25  $0 \leq z \leq 1.$

- The above formula therefore includes the case in which x is equal to 0 or 2, that is to say the case in which only a single metal cation is present, and also, 30 whether independent of the previous case or not, the case in which z is equal to 0 or 1, that is to say the case when only a single metal is present.

- A' may represent several metal cations and M' may also, 35 independently, represent several metals. A person skilled in the art knows how to rewrite formula (1) according to the number of components.

The presence of an oxygen superstoichiometry coefficient  $\delta$  with a value strictly greater than 0 advantageously contributes to the ionic conductivity of the material.

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According to one particularly preferred embodiment of the invention, M and M' are of mixed valency, that is to say such materials advantageously contribute to the electronic conductivity of the material.

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Advantageously, such materials according to the invention exhibit good thermal stability in terms of composition. This has been shown by TGA (thermogravimetric analysis) in air and verified by  
15 X-ray diffraction at temperature on two materials according to the invention which are  $\text{Nd}_{1.95}\text{NiO}_{4+\delta}$  and  $\text{Nd}_{1.90}\text{NiO}_{4+\delta}$ : measurement of the oxygen superstoichiometry coefficient  $\delta$  with respect to temperature, over a range from room temperature, i.e. about 20°C, up to 1000°C  
20 shows no sudden changes and confirms that the weight loss is directly and only proportional to the variation in the oxygen content of the material.

Advantageously, the A'' vacancies are distributed  
25 randomly. Electron diffraction patterns obtained by electron transmission microscopy of the material according to the invention, namely  $\text{Nd}_{1.90}\text{NiO}_{4+\delta}$ , reveal no elongation or smearing of the main (001) spots, showing perfect order along the c axis and the absence of  
30 intergrowth structures of the Ruddlesden-Popper type within the  $\text{A}_2\text{MO}_{4+\delta}$  stacks, thus confirming such a random distribution of the neodymium vacancies.

The term "lanthanide" is understood according to the  
35 invention to mean lanthanum La or an element of the group of lanthanides such as Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb or Lu and Y. The term "alkali metal" is understood according to the invention to mean an element excluding hydrogen from group 1

(IUPAC version) of the Periodic Table of the Elements. The term "alkaline-earth metal" is understood according to the invention to mean an element of group 2 (IUPAC version) of the Periodic Table of the Elements. The  
5 term "transition metal" is understood according to the invention to mean an element of groups 3 to 14 (IUPAC version) of the Periodic Table of the Elements, including of course elements of period 4, such as titanium Ti or gallium Ga, elements of period 5, such  
10 as zirconium Zr or tin Sn, and elements of period 6, such as tantalum Ta or mercury Hg. Preferably, according to the invention, the transition metal is an element of period 4.

15 The material according to the invention is advantageously characterized by very detailed measurements of one or more (A and/or A')/(M and/or M') ratios by using a Castaing microprobe (or EPMA, standing for Electron Probe Microanalysis) which make  
20 it possible to bring out the cation vacancy structure of said material.

In a preferred embodiment of the invention, said material is such that:

25 A and A' are independently chosen from the group formed by lanthanum La, praseodymium Pr, strontium Sr, calcium Ca and neodymium Nd, preferably neodymium Nd, strontium Sr and calcium Ca and even more preferably neodymium Nd, and such that:

30 M and M' are independently chosen from the group formed by chromium Cr, manganese Mn, iron Fe, cobalt Co, nickel Ni and copper Cu, preferably nickel Ni and copper Cu, and even more preferably nickel Ni.

35 In the particular cases according to the invention in which x is not equal to 0 or 2, and z is not equal to 0 or 1, the number of type A cations is at least two, namely A and A', and the number of type M cations is at least two, namely M and M'.

In such a case, preferably:

A is chosen from the group formed by lanthanum La, praseodymium Pr and neodymium Nd, preferably neodymium Nd; and

A' is chosen from the group formed by strontium Sr and calcium Ca, preferably calcium Ca;

M is chosen from the group formed by chromium Cr, manganese Mn, iron Fe, cobalt Co, nickel Ni and copper Cu, preferably nickel Ni; and

M' is chosen from the group formed by manganese Mn, iron Fe, copper Cu and cobalt Co, preferably copper Cu and manganese Mn.

In one particularly preferred embodiment according to the invention, the material has a crystallographic structure of  $K_2NiF_4$  type shown for example in "*Inorganic Crystal Structures*", page 30 by B G Hyde and S Anderson, Wiley Interscience Publication (1988). The structure is thus formed from layers of oxygen-containing octahedra  $MO_6$  shifted with respect to one another by  $\frac{1}{2} \frac{1}{2} \frac{1}{2}$ , A atoms ensuring cohesion between the layers and additional  $O_i$  oxygens possibly being inserted between these layers in vacant interstitial sites.

In a preferred embodiment, the material according to the invention possesses an oxygen surface exchange coefficient  $k$  of greater than  $1 \times 10^{-8}$  cm/s at  $500^\circ\text{C}$  and  $2 \times 10^{-6}$  cm/s at  $900^\circ\text{C}$  in the case of oxygen. The variation in said coefficient follows an Arrhenius law, which makes it easy to calculate this coefficient for another temperature in the temperature range of interest in the invention. This value is generally difficult to achieve with the existing materials used in fuel cells.

In a preferred embodiment, independently of the previous embodiment or not, the material according to

the invention possesses an electronic conductivity  $\sigma_e$  of at least 70 S/cm, preferably at least 80 S/cm and even more preferably greater than 90 S/cm at 700°C.

5 In a preferred embodiment, independently of the previous embodiment or not, the material according to the invention possesses an oxygen diffusion coefficient of greater than  $1 \times 10^{-9}$  cm<sup>2</sup>/s at 500°C and  $1 \times 10^{-7}$  cm<sup>2</sup>/s at 900°C. The variation in said  
10 coefficient follows an Arrhenius law, which makes it easy to calculate this coefficient for another temperature in the temperature range of interest to the invention. This value is generally not achievable in the case of the existing materials used in fuel cells.

15 In one preferred embodiment, the material according to the invention possesses an oxygen surface exchange coefficient  $k$  of greater than  $1 \times 10^{-8}$  cm/s at 500°C and  $2 \times 10^{-6}$  cm/s at 900°C in the case of oxygen, an  
20 electronic conductivity  $\sigma_e$  of at least 70 S/cm, preferably at least 80 S/cm and even more preferably greater than 90 S/cm at 700°C, and an oxygen diffusion coefficient of greater than  $1 \times 10^{-9}$  cm<sup>2</sup>/s at 500°C and  $1 \times 10^{-7}$  cm<sup>2</sup>/s at 900°C.

25 The invention also relates to an electrode comprising at least one material according to the invention.

Finally, the invention relates to a device for  
30 producing electrical energy, of the fuel cell type comprising at least one electrochemical cell comprising a solid electrolyte, an anode, and a cathode which is an electrode according to the invention. Said device also usually includes an anode interconnector and a  
35 cathode interconnector. Apart from the cathode, all the other components of said device are elements known to those skilled in the art.

Advantageously, the device according to the invention makes it possible to use the cathode according to the invention with both good electronic conductivity and good ionic conductivity, and also good thermal stability and sufficient efficiency from the industrial standpoint.

Finally, the invention relates to any process using such a device.

The invention also relates to the use of the electrode according to the invention as an oxygen pump electrode for gas purification.

Figures 1 to 3 serve to illustrate the invention, in a nonlimiting fashion, by comparative graphs.

Figure 1 is a graph showing, for various materials (a material according to the invention and two comparative materials), at various temperatures, the cathode overvoltage  $\Delta V$  in mV as a function of current density  $j$  (in mA/cm<sup>2</sup>).

Figure 2 is a graph showing, for various materials (two materials according to the invention and one comparative material), the oxygen diffusion coefficient  $D^*$  (in cm<sup>2</sup>/s) as a function of  $1000/T$  (in K<sup>-1</sup>), where  $T$  is the temperature.

Figure 3 is a graph showing, for various materials (two materials according to the invention and one comparative material), the oxygen surface exchange coefficient  $k$  (in cm/s) as a function of  $1000/T$  (in K<sup>-1</sup>), where  $T$  is the temperature.



### EXAMPLES

The following examples illustrate the invention without in any way limiting its scope.

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Two materials according to the invention were synthesized, namely  $\text{Nd}_{1.95}\text{NiO}_{4+\delta}$  and  $\text{Nd}_{1.96}\text{NiO}_{4+\delta}$ , having respective  $y$  values of 0.05 and 0.10. These materials were synthesized by solid-state reaction of  $\text{Nd}_2\text{O}_3$  and  
10  $\text{NiO}$  oxides at  $1100^\circ\text{C}$  or by mild chemical or sol-gel routes, for example from neodymium and nickel nitrates in solution. Their superstoichiometry values were  $\delta = 0.15$  and  $\delta = 0.06$  respectively, determined by an  $\text{Ni}^{3+}$  chemical analysis (iodometry).

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Their electronic conductivities  $\sigma_e$  measured at  $700^\circ\text{C}$  were 100 S/cm and 80 S/cm respectively. Their oxygen surface exchange coefficients  $k$  were  $5.5 \times 10^{-8}$  cm/s and  $1.7 \times 10^{-8}$  cm/s at  $500^\circ\text{C}$  respectively, and  
20  $5.5 \times 10^{-6}$  cm/s and  $1.7 \times 10^{-6}$  cm/s at  $900^\circ\text{C}$  respectively. Their oxygen diffusion coefficients were  $3.2 \times 10^{-9}$  and  $5.2 \times 10^{-9}$   $\text{cm}^2/\text{s}$  at  $500^\circ\text{C}$  respectively and  $3.5 \times 10^{-7}$  and  $2.5 \times 10^{-7}$   $\text{cm}^2/\text{s}$  at  $900^\circ\text{C}$  respectively. The percentage content of  $\text{Ni}^{3+}$  cations at  $700^\circ\text{C}$ ,  
25 determined by TGA (thermogravimetric analysis) in air, was 35% and 28% respectively. The variation in oxygen stoichiometry within this temperature range, in which the operating temperature of a fuel cell lies, was small and had no influence on the thermal expansion  
30 coefficient, which remained constant and equal to  $12.7 \times 10^{-6} \text{ K}^{-1}$ .

The electrochemical properties of these two materials according to the invention were evaluated in a  
35 three-electrode setup in a half-cell of the electrode material/YSZ/electrode material type in which the counterelectrode and the working electrode were symmetrical, these being painted onto the electrolyte and annealed at  $1100^\circ\text{C}$  for two hours. The platinum

reference electrode was placed far from the other two electrodes. The behavior of this material was analyzed under conditions close to those of an SOFC cell, that is to say under current and over a temperature range  
5 from 500 to 800°C. The measured cathode overvoltages had to be as low as possible. It was found, not surprisingly, that these overvoltages decreased strongly with temperature.

10 Figure 1 is a graph showing, for various materials (one material according to the invention and two comparative materials), at various temperatures, the cathode overvoltage  $\Delta V$  in mV as a function of  $j$  (in mA/cm<sup>2</sup>).

15 The cathode overvoltage of the material according to the invention with the particular composition  $\text{Nd}_{1.95}\text{NiO}_{4+\delta}$  was then compared with the cathode overvoltages of conventional materials, namely LSM ( $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ ) and LSF ( $\text{La}_{0.7}\text{Sr}_{0.3}\text{FeO}_3$ ) from data obtained from the  
20 literature (M Krumpelt et al., Proceedings European SOFC Forum (Lucerne 2002), published by J Huilsmans, Vol. 1, page 215). Figure 1 shows curves indicating, for the materials tested, at various temperatures, the cathode overvoltage in mV as a function of the current  
25 density  $j$  in mA/cm<sup>2</sup> of the current passing through the cell. This shows that, highly advantageously, the performance of the  $\text{Nd}_{1.95}\text{NiO}_{4+\delta}$  material according to the invention is superior to that of these materials used.

30 Figure 2 is a graph showing, for various materials (two materials according to the invention and one comparative material), the oxygen diffusion coefficient  $D^*$  (in cm<sup>2</sup>/s) as a function of  $1000/T$  (in K<sup>-1</sup>), where  $T$  is the temperature. Each curve is a straight line. The  
35 two materials according to the invention are  $\text{Nd}_{1.95}\text{NiO}_{4+\delta}$  and  $\text{Nd}_{1.90}\text{NiO}_{4+\delta}$ . The comparative material is  $\text{Nd}_2\text{NiO}_{4+\delta}$ , that is to say a material with an oxygen superstoichiometry but no cation vacancy. It may be seen that, within the temperature range of interest to

the invention, the materials according to the invention generally have, to within the measurement error, a higher coefficient  $D^*$ , and are therefore more useful. Figure 2 also shows the straight line indicating the  
5 minimum  $D^*$ , or  $D^*_{\min}$ , according to the invention.

Figure 3 is a graph showing, for various materials (two materials according to the invention and one comparative material), the oxygen surface exchange  
10 coefficient  $k$  (in cm/s) as a function of  $1000/T$  (in  $K^{-1}$ ), where  $T$  is the temperature. Each curve is a straight line. The two materials according to the invention are  $Nd_{1.95}NiO_{4+\delta}$  and  $Nd_{1.90}NiO_{4+\delta}$ . The comparative material is  $Nd_2NiO_{4+\delta}$ , i.e. a material with an oxygen  
15 superstoichiometry but no cation vacancy. It may be seen that, within the temperature range of interest to the invention, the materials according to the invention have a higher coefficient  $k$ , and are therefore more useful. Figure 3 also shows the straight line  
20 indicating the minimum  $D^*$ , or  $D^*_{\min}$ , according to the invention.